

Towards Energy Auto-Tuning

Sebastian Götz, Claas Wilke, Matthias Schmidt, Sebastian Cech and Uwe Assmann

sebastian.goetz@acm.org, {claas.wilke, matthias.schmidt, sebastian.cech, uwe.assmann}@tu-dresden.de

Technische Universität Dresden, Department of Computer Science, Software Technology Group, D-01062 Dresden

Abstract—Energy efficiency is gaining more and more importance, since well-known ecological reasons lead to rising energy costs. In consequence, energy consumption is now also an important economical criterion. Energy consumption of single hardware resources has been thoroughly optimized for years. Now software becomes the major target of energy optimization. In this paper we introduce an approach called energy auto-tuning (EAT), which optimizes energy efficiency of software systems running on multiple resources. The optimization of more than one resource leads to higher energy savings, because communication costs can be taken into account. E.g., if two components run on the same resource, the communication costs are likely to be less, compared to be running on different resources. The best results can be achieved in heterogeneous environments as different resource characteristics enlarge the synergy effects gainable by our optimization technique. EAT software systems derive all possible distributions of themselves on a given set of hardware resources and reconfigure themselves to achieve the lowest energy consumption possible at any time. In this paper we describe our software architecture to implement EAT.

I. INTRODUCTION

The energy use of servers is steadily raising and soon will pass the asset costs as the U.S. Environmental Protection Agency (EPA) shows in their report on server and data center energy efficiency [1]. According to this report, the energy consumption of servers doubled from year 2000 to 2006 and will double again until 2011. More than 100 billion kWh (approx. \$7.4 billion) will be the annual electricity consumption in the U.S. in 2011. The EPA recommends research and development activities to improve the energy efficiency of servers and also points out the necessity to investigate potential savings by power management across multiple resources [1, p. 118].

The energy used by hardware resources should be proportional to their utility for end users. In other words, if the end user does not utilize resources by using software running on top of them, the resources should not use any energy. This issue is known under the term of *energy proportionality* [2]. Recent work shows that we are far from energy proportionality. In [3] Tsirogiannis et. al. reveal that over 50% of the overall power consumption is caused by servers with idle load. Moreover, they detected that resource utilization does not directly correlate to its energy use. The actual energy use depends on the kind of task the resource has to accomplish. They show a 60% variation of power consumption for the same level of resource utilization. These results substantiate the nonexistence of energy proportionality. (On the other hand they show, that energy is proportional to performance, having idle power as offsets). Tsirogiannis et. al. point out the optimization of multiple, jointly used resources as a promising

direction, too [3, p. 242].

Several problems derive from the energy-unawareness of IT infrastructures used to run distributed software. First, the energy consumption of software components is hard to predict. This is, because energy consumption of software components depends on the hardware they are running on and the user that interacts with the components. The users demand as well as the users utility w.r.t. service requests need to be considered. Energy efficiency is the balance between user utility and energy consumption. However, resource usage by software components and the user's workload are not explicitly taken into account in current software development processes. Hence, to predict energy consumption of software components and correlate it with user's requirements, an energy-aware software architecture and runtime environment are required.

In this paper we introduce an approach for *energy auto-tuning (EAT)* software systems. Such systems derive all possible distributions of their software on a given set of hardware resources and reconfigure themselves to achieve the lowest energy consumption possible at any time. Our focus are distributed, component-based applications. We therefore propose the *Cool Component Model (CCM)* together with the *Energy Contract Language (ECL)* as appropriate means to capture energy-aware software architectures. Furthermore, we propose the *THEATRE* as our energy-aware runtime environment. We thus also investigate a development process for energy-aware software systems and do not solely focus on energy auto-tuning. This is, because energy auto-tuning requires such an energy-aware software architecture.

The rest of this paper is structured as follows. In Section II we introduce a running example. Afterwards, we highlight requirements for EAT systems in Section III. Our proposed software architecture and runtime environment are presented in Section IV. Finally, we outline related work in Section V and conclude and give pointers for future work in Section VI.

II. VIDEO SERVER EXAMPLE

In this section we present an example of a small component-based system that can be energy-optimized using EAT. The example was adapted from a case study depicted in [4]. It describes a simple video server scenario consisting of two software components: a *VideoServer* and a *VideoPlayer* (cf. Fig. 1). The *VideoServer* is located at a server whereas the *VideoPlayer* is deployed at clients. The *VideoServer* provides services to select and transmit videos that are stored on a *FileServer*. The *VideoPlayer* can receive video streams via a network

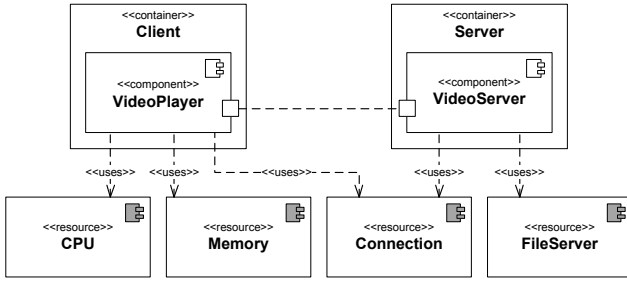


Fig. 1. The components of the VideoServer example; cf. [4].

Connection, decodes the video frames and displays them on the screen.

Besides software components, hardware resources are involved in the presentation of a video. First, the VideoServer requires a FileServer to select and deliver file streams to clients. Furthermore, a network Connection is required. On the client side, CPU and Memory are used to decode and display the video. One may argue, that further resources like a monitor and speakers are required to present the video. Anyhow, the example was designed to illustrate the concepts and thus, remained as simple as possible.

Different clients require to display videos in different qualities, e.g., a mobile phone does not require the same resolution as a desktop PC. Hence, the VideoServer and the VideoPlayer provide their services in different qualities that can differ in resolution and frame rate. Resources can provide different quality profiles for their services as well. E.g., a Connection can provide different bandwidths, or a Memory unit can provide different amounts of space. Using these quality profiles in combination with component-to-component and component-to-resource dependencies allows to switch between different configurations of the system at runtime. E.g., the application could use a low-quality resolution if a video was requested from a mobile phone to save bandwidth, CPU and, most importantly to us, energy.

III. REQUIREMENTS FOR EAT SYSTEMS

After giving a running example we now highlight requirements for an EAT system, which can be classified into component modeling facilities, expressing hardware/software dependencies and requirements regarding an energy-aware runtime environment. These requirements are the basis for our main contributions, namely the CCM component model, the ECL contract language and the energy-aware runtime environment THEATRE.

A. Modeling of Software and Hardware Components

An EAT system requires a special software architecture, whose building blocks are explicitly connected to resources. With resources, we do not just denote hardware resources, like a central processing unit, but virtual resources, like operating systems and files, too. We propose *components* [5] to describe both, software and hardware elements of an EAT architecture.

Furthermore, our proposed component model CCM has to fulfill the following requirements:

1) *HW-SW modeling*: Software only consumes energy in an indirect way by using hardware resources where the software components run, i.e. the hardware consumes energy by executing software components. In order to increase energy efficiency of IT infrastructures, it is not sufficient to capture the architecture of software components. It is also necessary to take hardware resources of the infrastructure into account.

2) *Quality-of-Service (QoS) properties*: The component model should also provide facilities to express quality of service properties of hardware and software components (e.g., energy consumption of a CPU). Such QoS properties are the basis for optimizing energy efficiency at runtime.

3) *Variant modeling*: Each component of an EAT architecture can exist in different implementation variants with a common interface. Offered services from the component can differ in quality and therefore in the energy consumption of their underlying hardware. Hence, the CCM has to provide concepts to express implementation variants of software components including implementation specific QoS properties.

4) *Behavior modeling*: Hardware components are able to reside in different performance states (e.g., as defined in the ACPI specification [6]). Each performance state implies a specific energy consumption of hardware resources. Such performance states as well as the underlying behavior should be regarded in a suitable component model. Behavior modeling of software components is also necessary because it implies which hardware resources are used by a component.

B. Modeling of Software/Hardware Dependencies

Besides defining central building blocks of software, a software architecture defines, how these building blocks are connected to each other. Due to the different variants of provided and required services we propose to use contracts as connectors for components. They can be realized by our contract language ECL, which has the following requirements:

1) *Dependencies between components*: The contract language should be able to express dependencies between different software components and between software components and required resources.

2) *Energy Consumption*: The contract language should allow to define energy consumption of resources according to their current state. The energy consumption of software components should be computable via their component and resource dependencies. Energy consumption, which is not caused by running software on resources, e.g. of resources in idle mode, is described in the behavior part of the component model.

3) *Quality Modeling*: Besides energy consumption, the contract language should support other functional and/or non-functional requirements for components and resources (e.g., qualities like frame rates, response times and resolutions).

4) *Variant modeling*: Similar to the component model the contract language should allow to describe different states for components that lead to different QoS for provided and required services.

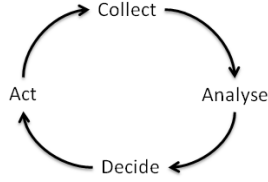


Fig. 2. Autonomic Control Loop of auto-tuning Systems, cf. [7]

C. Energy Auto-Tuning Runtime Environment

Components, with explicitly defined resource usage, do not improve energy efficiency on their own. The problem is, that there is no energy-aware authority that manages requests of software on hardware. Such an authority is our proposed *THree-layer Energy auto-tuning Runtime Environment (THE-ATRE)*. To optimize the efficiency of software systems w.r.t. user requests and energy consumption the authority needs to enforce the best system configuration for current and forthcoming user requests. A system configuration describes which component implementations are being used and at which resources the corresponding instances are deployed. Therefore, THEATRE has to fulfill four requirements conforming to the autonomic control loop principle of auto-tuning systems [7], which is depicted in Fig. 2.

1) *Collect*: The EAT system should be aware of the existing software components and hardware resources (either directly or indirectly via hierarchies of sub-systems).

2) *Analyze*: For every user request, the EAT system should be able to analyze the request according to its required components, resources and, in consequence, its energy consumption. All possible deployments of the required components should be computed and evaluated w.r.t. their energy consumption.

3) *Decide*: The EAT system should select the energy-optimal configuration for current and future service requests.

4) *Act*: Finally, the EAT system must be able to reconfigure the system according to the energy-optimal configuration computed before.

IV. ENERGY AUTO-TUNING SYSTEMS

This section elaborates on our energy-aware software architecture, which consists of our proposed component model and contract language, and our energy auto-tuning runtime environment (THEATRE).

A. An Energy-aware Software Architecture

According to the requirements presented above, our proposed software architecture consists of components and contracts, which are described in the following.

1) *Components*: To model the parts of an IT infrastructure (user, hardware resources and software components) we designed the *Cool Component Model (CCM)*. CCM extends and combines ideas of the SPEEDS meta model [8] and the MADAM component model [9] to allow modeling of a system's structure, behavior and energy consumption. Besides these three aspects, defining variations is a major concern in CCM. As the definition of energy consumption will be

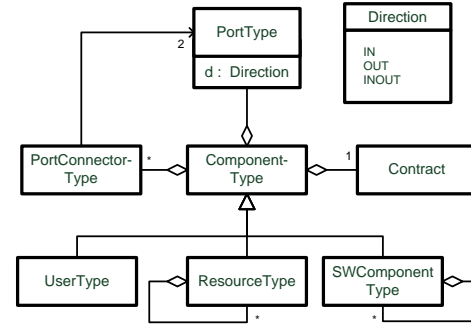


Fig. 3. The structure package of CCM

discussed in Section IV-A2, this section will focus on structure, behavior and variation modeling. For each of these three aspects our component model has an own package. Nevertheless, these packages cannot be seen as distinct parts, but are interconnected.

To model the structure of a system CCM provides concepts which are grouped in the *structure package* illustrated in Fig. 3. This package can be used to define a hierarchical IT infrastructure, its interfaces, interactions between interfaces as well as contracts that are valid between them. Furthermore, it acts as a type system for architectural concepts in CCM. These types can be used later on to define variations of specific parts of the system to allow energy auto-tuning.

A central concept in CCM are components, which are represented by *ComponentTypes* in the structure package. *UserType*, *ResourceType* and *SWComponentType* are specific components referring the different parts of an IT infrastructure, where the latter two concepts form a hierarchy using self containments. Furthermore, *ComponentTypes* contain a number of *PortTypes*, which define the component's external interface. A *PortType* contains a *Direction* to specify whether the component offers (OUT) or requires (IN) a service via this port or if it does both (INOUT). *PortConnectorTypes* enable components to combine (sub)components via their ports and model interactions in this way. Finally a *ComponentType* has a *Contract* that specifies what the component requires and provides.

To model behavior, CCM provides concepts which are contained in the *behavior package* presented in Fig. 4. This package can be used to define a behavior template of a component and workloads that invoke this behavior at certain points in time. Modeling the behavior is of special importance to the components and resource simulation (see Sec. IV-B) as it allows to define energy consumption over time. The central concept of the behavior package is the *BehaviorTemplate*. It defines the behavior of a component and contains *CostParameters* which need to be substituted by a concrete variant of the component. For instance, a *BehaviorTemplate* can be a *StateMachine* while states and transitions might contain energy consumption or time as *CostParameters*. Moreover, additional subclasses of *BehaviorTemplates* like heuristics are possible. Each

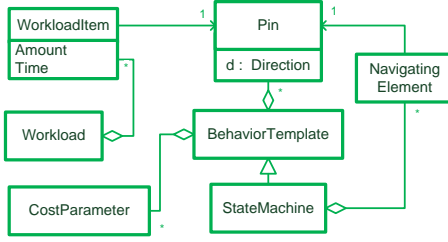


Fig. 4. The behavior package of CCM

BehaviorTemplate contains Pins which are equivalent to Ports in the structure package. A Pin defines the external interface of a BehaviorTemplate and is connected via NavigatingElements to parts of the StateMachine. Later on, a concrete variant of a component connects a pin with a port and that way can model what happens if the service of a port gets invoked.

To model variation, CCM provides concepts which are contained in the *variation package* depicted in Fig. 5. This package can be used to define concrete variants of components by connecting one ComponentType to one BehaviorTemplate and substituting its parameters. Furthermore, it allows to define variants of complete (sub)systems which can be used by THEATRE to decide which system configuration fits to the user's needs and in that way is the most energy efficient. Central to the variation package are the concepts Component and Behavior. A Component refers to a ComponentType and can be specialized in the same way (User, Resource, SWComponent - not depicted in Fig. 5). Furthermore, it contains Ports and PortConnectors, which refer to their types respectively. These two concepts and the ability to define sub-variants allow to specify complex variations of complete systems. The Behavior refers to a BehaviorTemplate and substitutes its cost parameters using CostParameterSubstitutions. Finally, a Behavior owns Links that connect Ports of the component variant to Pins of the BehaviorTemplate.

Given the three packages *structure*, *behavior* and *variation* CCM provides advantages regarding the following three aspects. First, it allows to specify the architecture of software components and resources and hence to build a repository of IT infrastructure parts. Second, it allows to define behavior independently of a component's structure and in that way increases reuse. Third, CCM provides concepts to model alternatives, which enables THEATRE to find the most energy efficient system configuration.

2) *Contracts*: To describe and compute the energy consumption of software components, we use the *Energy Contract Language (ECL)*. ECL is an advancement of the *Component Quality Modeling Language (CQML)* [10] and *CQML+* [11] w.r.t. energy consumption. ECL allows to define QoS-contracts using characteristics, qualities and profiles for resources and software components. ECL contains the description of the dependencies between software components and resources and

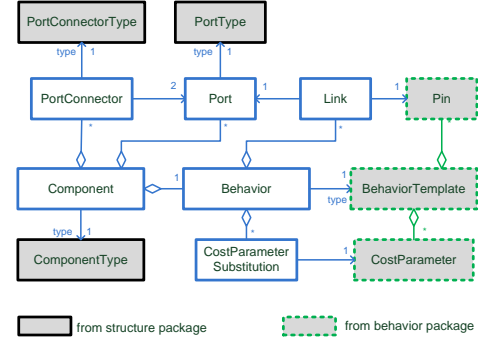


Fig. 5. The variation package of CCM

the variability of these compositions.

Characteristics are measuring units used to express qualities in profiles. E.g., the frameRate of a VideoStream can be specified as shown below, defining the type of frameRate and how its values are derived from VideoStreams.

```

1 characteristic frameRate(stream:VideoStream) {
2   domain numeric integer frames/second;
3   value stream.getFrameRate();
4 }

```

The major concept of ECL are profiles that specify the different states of resources and software components. E.g., the resource Network has two different states which are connected and disconnected:

```

1 profile NetworkStates for Network {
2   state connected {
3     energy-effect 0.8 Watt;
4     provides characteristic bandwidth = 600;
5   }
6   state disconnected {
7     energy-effect 0.4 Watt;
8   }
9   transition connected -> disconnected {
10    whenever event-occurs disconnect();
11    delay 1.0 seconds;
12    energy-effect 5.0 Watt;
13  }
14  transition disconnected -> connected {
15    whenever event-occurs send();
16    delay 10.0 seconds;
17    energy-effect 30.0 Watt;
18  }
19  initial-state disconnected;
20 }

```

The different profile states contain an energy-effect that specifies, how much energy is consumed for a resource being in this state. Optionally, a state can provide characteristics for software components using this resources, such as the bandwidth provided in the connected state. Transitions between profile states can be defined specifying their duration and energy-cost. Events declare when such transitions should be performed. Finally, profiles for resources have to specify an initial-state for their instances.

Besides profiles for resources, profiles have to be defined for software components as well. Below, a profile for the VideoServer component introduced in Sec. II is shown:

```

1  profile ServerProfile for VideoServer {
2    state highQuality {
3      uses characteristic bandwidth = 450;
4      provides characteristic frameRate = 30
5        and characteristic imageWidth = 352
6        and characteristic imageHeight = 288;
7    }
8    state lowQuality {
9      uses characteristic bandwidth = 150;
10     provides characteristic frameRate = 10
11       and characteristic imageWidth = 176
12       and characteristic imageHeight = 144;
13   }
14   transition any-state -> any-state {}
15   precedence highQuality, lowQuality;
16 }

```

As specified, the `VideoServer` provides two different states, these are a `highQuality` and a `lowQuality` state. The states differ in the resolution (`imageWidth` and `imageHeight`) and `frameRate` of their provided video stream. Besides the provided resolution and frame rate, both states require a characteristic bandwidth provided by Network resources. But as expected, the `highQuality` requires a higher amount of bandwidth than the `lowQuality` state. The `VideoServer` profile is now used as a basis for a profile of the `VideoPlayer` introduced in Section II:

```

1  profile PlayerProfile for VideoPlayer {
2    state highQuality {
3      uses profile ServerProfile :: highQuality
4      and characteristic bandwidth = 450
5      and characteristic cpu_usage = 66.7
6      and characteristic ram = 200.0;
7      provides characteristic frameRate = 30
8      and characteristic image_width = 352
9      and characteristic image_height = 288;
10   }
11   state lowQuality {
12     uses profile ServerProfile :: lowQuality
13     and characteristic bandwidth = 150
14     and characteristic cpu_usage = 25.0
15     and characteristic ram = 50.0;
16     provides characteristic frameRate = 10
17     and characteristic image_width = 176
18     and characteristic image_height = 144;
19     resources
20   }
21   transition any-state -> any-state
22 }

```

Like the `VideoServer`, the `VideoPlayer` provides two different states `highQuality` and `lowQuality`. As illustrated above, the states provide the same qualities as the `VideoServer`, but require a specific state of the `VideoServer` to provide their own service. This dependency information is required to specify, which components can be deployed and composed to provide specific QoS at runtime. Required resources can be reserved; the resource profiles can be used to predict the energy consumption of a specific provided software service. Currently, ECL is still in an early development state. Initial tool support, including a text editor with editing support like syntax highlighting and code completion, has been realized using *EMFText* [12].

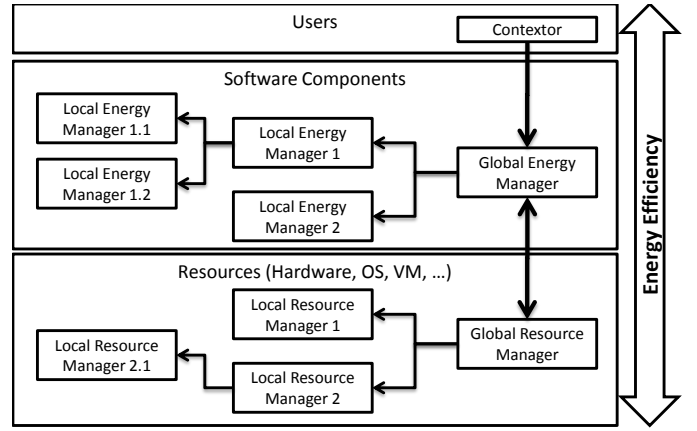


Fig. 6. General Architecture of THEATRE - THree layer Energy Auto Tuning Runtime Environment

B. THEATRE - A Runtime Environment for Energy Efficient Distributed, Component-based Software Systems

Using software components and contracts to design and implement software systems does not lead to better energy efficiency on its own. Instead the knowledge about the different system variants, along with their cost and utility, needs to be used by a runtime environment, which is able to reconfigure the running system. The decision, which variant is best, depends on the user's needs, which vary over time. In consequence, the best alternative is known only at runtime and is likely to change over time. A system variant denotes a mapping of specified component implementations onto resources.

We propose to use a runtime environment, which consists of three layers: a *user*, *software* and *resource* layer as depicted in Fig. 6. On the user layer *contextors* are used, to collect data about the user's needs. Analogously, on the resource layer, *resource managers* are used, to collect information about the energy behavior of resources. It is important to note that resources are not just hardware resources, but complex, virtual resources, like the operating system or files. The centered layer comprises software components and *energy managers*, which use the knowledge of contextors, resource managers and their own knowledge about existing components and their variations (implementations), to choose the currently most energy efficient system variant. If the energy manager decides on a system variant, which is not the current, it forces a re-configuration. This includes the migration of components from one resource to another. In consequence, resource managers need to provide functionality to steer resources. For example, when a resource is unused, after the last software component has migrated somewhere else, it should be powered down in order to save energy. In the following, each layer is examined in more detail.

1) *User layer*: To reason about the user's utility, the expectations of the user need to be collected by so-called *contextors*. User utility can be quantified using *user metrics* [13] – human-perceptible qualities of software, like response time or resolution. The easiest way to collect information about the user's

expectations is by letting the user define her expectations explicitly. A well known example is the 'high quality' button of the YouTube video player, which allows the user to state that she expects to see a video in high quality. More sophisticated approaches, like using an ontology to define user-metrics and probabilistic or heuristic approaches to predict the user's expectations can be used as well. Additionally, the user's demand need to be predicted or collected by the contexter. This is, because the demand determines which software components are required.

2) *Resource layer*: The resource layer comprises hierarchical interconnected resources, in which each has a dedicated *resource manager*. This manager has to fulfill five requirements. First, it needs to know about the infrastructure. That is, which other resources can be reached. Second, it needs to know about its resource's properties: What services does the resource offer? What energy states does the resource have? Third, it needs to be able to predict the energy behavior for a workload, which is a timed sequence of service requests. We use a simulation approach, based on *energy state charts* (ESC) [14], to realize the prediction. The central feature of ESCs is, that states have a defined power consumption rate and transitions have defined delays as well as energy costs. Various other approaches exist. Flinn et. al. use models of linear functions [15] and Fei et. al. use heuristics [16]. Models of linear functions and heuristics only provide a possibly good prediction, whereas ESCs allow for predictions, which are as precise as the parameters provided to the charts. Therefore we decided to use ESCs. Last, the resource manager needs to be able to steer the resource and force it into some other energy state. At least, it should offer to switch off the resource and to switch it on again. We distinguish between a *global resource manager* and *local resource managers*. Whereas local resource managers are tied to their resource, the global resource manager abstracts the whole infrastructure. In [17] we elaborate on resource managers.

3) *Software layer*: The software layer comprises software components and *energy managers*, which reason about valid system variants of the software. In other words, the energy manager assesses mappings of component implementations to resources with energy usage as cost and the fulfillment of user expectations as utility. The system variant with the best combination of cost and utility will be chosen by the manager, which then forces a reconfiguration of the system, if necessary. We distinguish between a *global energy manager* and *local energy managers*. The local managers are tied to software components and know about their composability by using the ECL contracts specified during software development. The global energy manager knows the local ones and uses their information about valid mappings (system variants) to combine it with energy usage information from the resource layer and utility information from the user layer. It directly communicates with the global resource manager. If a reconfiguration was forced, the utilization of resources changes and might fall below or above thresholds. In consequence, these resources should be forced into another energy state,

like a sleep or special performance mode. It is important, that the global energy manager considers the energy required to process the reconfiguration. This is, because reconfigurations swiftly become very energy consuming, for example due to the need to initialize new resources.

In conclusion, information of all three layers is used by the global energy manager which steadily initiates reconfigurations of the system to keep the highest possible ratio of utility and cost (i.e. energy efficiency) at any time.

V. RELATED WORK

In this section we outline related work from three research areas, which we combined in our overall approach. These areas are: auto-tuning techniques, approaches for energy efficiency in general and quality-aware component models.

A. Auto-Tuning

auto-tuning is a well established optimization technique in the *high performance computing (HPC)* community. Running numerical algorithms (e.g., for matrix multiplication or Fourier transform) near to the peak performance of parallel computers is an important goal in HPC. The performance of a numerical algorithm's implementation depends strongly on its underlying hardware platform as well as the problem size (e.g., matrix size). Therefore, platform specific as well as problem specific optimizations are necessary for such algorithms.

During recent years, several successful numerical libraries with auto-tuning facilities have been developed [18], [19], [20], [21], [22]. *auto-tuning capability* means that libraries are able to adapt themselves to specific hardware architectures. Approaches behind these libraries can be distinguished between optimization at installation time and optimization at runtime. Libraries with optimization facilities at installation time (e.g., *ATLAS* [18], *PhiPac* [21], *Spiral* [22]) analyze properties of a target platform to generate highly optimized code. For instance, in *ATLAS* analyses are realized based on certain hardware parameters (e.g., capacity of L1 data cache, number of registers) to determine additional parameters like loop unrolling factors for the following code generation phase. Generated code is then executed for benchmarking purposes. Achieved MFLOPS are traced back into the analysis component of *ATLAS*. Other auto-tuning libraries like *OSKI* [20] optimize not only the implementation code but provide also optimized data structures. Optimization at runtime is for instance provided by *FFTW* [19], which can be used for Fourier transform. *FFTW* provides a set of optimized composable code blocks (codelets) performing a specific part of transform. An optimized transform is created by composing several codelets to a so called plan. Internally plan generation is realized by measuring the performance of available plans and selecting the fastest implementation. For executing a plan *FFTW* provides a separate executor.

The commonality behind the auto-tuning approaches mentioned above is the autonomic control loop principle [7]. As explained in Section III we consider this principle as a

main requirement for our energy-aware runtime environment THEATRE.

B. Approaches for Energy Efficiency

The energy efficient coordination of software applications on mobile devices has been investigated by Yunsu Fei et. al. [16]. Like low-power states of hardware resources, they target low-power states of software applications, based QoS constraints. They specify QoS as human-perceptible characteristics of applications. E.g., for a video player these are framerate, framesize and dither (color/gray/...). The aim of the authors' work is to energy efficiently run multiple applications on a single mobile device, whereby the user's intension (utility) is regarded in terms of priorities set by the user.

Their approach is a middleware tier sitting on top of the operating system (OS). The OS needs to provide a *process manager*, which knows about all running processes, and a *resource manager*, which is able to monitor hardware resources (at least the battery). However, if the resource managers would have control over resources, higher energy savings could be achieved by, for example, powering down unused resources. Our approach goes further than Fei's in that it targets multiple applications running on *multiple* mobile and stationary devices. It will furthermore provide a more powerful mechanism for multi dimensional QoS.

Jason Flinn et. al. investigated energy efficiency of mobile devices, too [15]. Their focus was on the decision, whether a method shall be run on a mobile phone or remotely on a server. To measure resource usage, the */proc* file system and special drivers are used. To predict resource usage and demand Flinn et. al. use mathematical models (linear and more complex), which are approximated for the near future. The decision, where to run a method, is made by a heuristic solver, which looks for an optimal trade-off between the user's utility and the required energy usage. Because the solver uses heuristics, it does not always make the best decision. Our approach differs from Flinn's in the way that we focus on the decision where to deploy interconnected software components and which implementations of them shall be used.

Chiyoung Seo et. al. [23] compared software architecture styles for distributed software systems in regard to their energy consumption. They developed an energy estimation framework, which does not only consider energy used due to computation, but also energy used for communication. In contrast to other approaches, Seo et. al. measured how much energy was consumed by instructions on the level of the virtual machine and derived the total energy use based on this data. Notably, only energy costs were taken into account. The end user's utility, and thus energy efficiency, were not examined by their approach. Nevertheless, we follow Seo's proposal to consider energy use due to communication, too.

C. Quality aware component models

The *Palladio component model (PCM)* [24] focuses the performance point of view of component based software architectures. It provides concepts for modeling hardware and soft-

ware in order to analyze and evaluate systems' performance. Facilities for modeling QoS properties are limited regarding the performance perspective, i.e. energy consumption of hardware resources can not be expressed. Since PCM is used for analyzing concrete system architectures it is not possible to model component variants. Behavior modeling is provided by so called *service effect specifications*, however, just from a performance point of view. Ongoing research towards self-aware performance and resource management techniques is part of the *Descartes* research project, which was started in 2009. Kounev et. al. [25] aim for developing a runtime system that is able to predict the runtime performance of a software application using PCM. Based on these predictions an online reconfiguration process is invoked in order to fit performance requirements of the application. Improving energy efficiency is also addressed by authors however only from a performance point of view. In contrast, our focus is to improve energy efficiency by focusing the user's utility.

Geijs et. al. developed a component model for self-adaptive applications on mobile devices [9] in the *MADAM* project. In this component model hardware and software components can be modeled including their QoS properties and implementation variants of components. Describing energy consumption of hardware resources is possible in a limited manner because the component model does not provide concepts for specifying component behavior (e.g., energy behavior of hardware).

The *SPEEDS meta model* [8] was developed in the European SPEEDS project and allows to model component-based embedded systems. Therefore, it offers concepts to specify hardware, software and behavior. As SPEEDS was designed for reuse, it provides variation to some degree, but doesn't support explicit runtime variants. Finally SPEEDS allows to model QoS properties in a contract language. But, even though SPEEDS models multi dimensional QoS with so called view points, only qualities like performance or functionality can be part of contracts. For energy modeling there isn't any view point available. Nevertheless, as SPEEDS is a mature component model we decided to reuse selected concepts in our own energy-aware component model.

In [26], Göbel et al. presented a component model for a QoS scheduling component environment developed during the *COMQUAD* project. Their component model separates components into component specification, component implementation, installed components and component objects. Although dependencies between software components and hardware resources can be described using QoS contracts specified in *CQML+* [11], resources are not modeled in the component model but are only defined in the *CQML+* contracts. At runtime a *resource manager* is responsible to allocate and deallocate resources required by software components to provide their QoS.

VI. CONCLUSION AND FUTURE WORK

In this paper we introduced our energy-aware software architecture. We showed, that bridging the gap between user utility and energy consumption requires a component-based

architecture with contracts as connectors. Based on this architecture we introduced THEATRE: the three-layer energy auto tuning runtime environment. The aim of this runtime environment is to keep the best ratio of user utility and energy consumption for a distributed, component-based software system.

As mentioned, our work is at an early stage. Many concepts have not been tested yet and will require further testing, refinement and evaluation. This includes a design of contextors, collecting the user's QoS requirements and deriving energy utility functions required to parameterize THEATRE.

Yet, first parts of our energy-aware software architecture and THEATRE have been implemented, including a first parser for ECL contracts and a simulator for resource energy profiles. These first investigations show promising results. Nevertheless, the feasibility of our approach requires further investigation and evaluation. For future work we plan to evaluate THEATRE using multiple case studies, including the presented video server example, cloud computing applications and simple algorithms having multiple implementations varying in QoS (e.g., sorting algorithms). We plan to measure the energy consumption of whole computer systems and single hardware resources and to compare these results with our predicted energy consumption based on CCM models and ECL contracts.

ACKNOWLEDGMENT

The authors thank their colleagues J. Waltsgott, R. Fritzsche and Prof. K. Meißner of the research project CoolSoftware,¹ part of the CoolSilicon Spitzencluster, funded by the Bundesministerium für Bildung und Forschung (BMBF).

REFERENCES

- [1] U.S. Environmental Protection Agency, ENERGY STAR Program, "Report to congress on server and data center energy efficiency public law 109-431," http://www.energystar.gov/ia/partners/prod_development/downloads/EPA_Datacenter_Report_Congress_Final1.pdf, 2007.
- [2] L. A. Barroso and U. Hözlze, "The case for energy-proportional computing," *Computer*, vol. 40, no. 12, pp. 33–37, 2007.
- [3] D. Tsirogiannis, S. Harizopoulos, and M. A. Shah, "Analyzing the energy efficiency of a database server," in *SIGMOD '10: Proceedings of the 2010 international conference on Management of data*. New York, NY, USA: ACM, 2010, pp. 231–242.
- [4] M. Mulugeta Dinku, "Qos contract negotiation in distributed component-based software," Ph.D. dissertation, Technische Universität Dresden, Dresden, Germany, July 2007.
- [5] C. Szyperski, D. Gruntz, and S. Murer, *Component Software Beyond Object-Oriented Programming*, C. Szyperski, Ed. Addison-Wesley and ACM Press, 1999.
- [6] Hewlett-Packard, Intel, Microsoft, P. Technologies, and Toshiba, "Advanced configuration and power interface specification, revision 4.0a," <http://www.acpi.info/spec.htm>, April 2010.
- [7] S. Dobson, S. Denazis, A. Fernández, D. Gaïti, E. Gelenbe, F. Massacci, P. Nixon, F. Saffre, N. Schmidt, and F. Zambonelli, "A survey of autonomic communications," *ACM Trans. Auton. Adapt. Syst.*, vol. 1, no. 2, pp. 223–259, 2006.
- [8] The SPEEDS Consortium, "D.2.1.5 speeds 1-1 meta-model," http://speeds.eu.com/downloads/SPEEDS_Meta-Model.pdf, May 2009.
- [9] K. Geihs, M. U. Khan, R. Reichle, A. Solberg, and S. O. Hallsteinsen, "Modeling of component-based self-adapting context-aware applications for mobile devices," in *SET*, ser. IFIP, K. Sacha, Ed., vol. 227. Berlin/Heidelberg, Germany: Springer, 2006, pp. 85–96.
- [10] J. O. Aagedal, "Quality of service support in development of distributed systems," Ph.D. dissertation, University of Oslo, Norway, 2001.
- [11] S. Röttger and S. Zschaler, "Cqml+: Enhancements to cqml," in *Proceedings of the 1st International Workshop on Quality of Service in Component-Based Software Engineering*. Toulouse, France: Cépaduès-Éditions, 2003, pp. 43–56.
- [12] F. Heidenreich, J. Johannes, S. Karol, M. Seifert, and C. Wende, "Derivation and refinement of textual syntax for models," in *Model Driven Architecture - Foundations and Applications*, ser. LNCS, R. F. Paige, A. Hartman, and A. Rensink, Eds., vol. 5562. Berlin/Heidelberg, Germany: Springer, Juni 2009, pp. 114–129.
- [13] J. Flinn and M. Satyanarayanan, "Managing battery lifetime with energy-aware adaptation," *ACM Trans. Comput. Syst.*, vol. 22, no. 2, pp. 137–179, 2004.
- [14] L. Benini, R. Hodgson, and P. Siegel, "System-level power estimation and optimization," in *Proceedings of the International Symposium on Low Power Electronics and Design (ISLPED-98)*. New York: ACM Press, Aug. 10–12 1998, pp. 173–178.
- [15] J. Flinn, S. Park, and M. Satyanarayanan, "Balancing performance, energy, and quality in pervasive computing," in *ICDCS '02: Proceedings of the 22nd International Conference on Distributed Computing Systems (ICDCS'02)*. Washington, DC, USA: IEEE Computer Society, 2002, p. 217.
- [16] Y. Fei, L. Zhong, and N. K. Jha, "An energy-aware framework for dynamic software management in mobile computing systems," *ACM Trans. Embed. Comput. Syst.*, vol. 7, no. 3, pp. 1–31, 2008.
- [17] S. Götz, C. Wilke, M. Schmidt, S. Cech, J. Waltsgott, and R. Fritzsche, "THEATRE resource manager interface specification," Technische Universität Dresden, Dresden, Germany, Tech. Rep., To be published in 2010.
- [18] R. C. Whaley and J. Dongarra, "Automatically Tuned Linear Algebra Software," University of Tennessee, Knoxville, TN, USA, Tech. Rep. UT-CS-97-366, December 1997.
- [19] M. Frigo and S. G. Johnson, "FFTW: An adaptive software architecture for the FFT," in *Proc. 1998 IEEE Intl. Conf. Acoustics Speech and Signal Processing*, vol. 3. Washington, DC, USA: IEEE Computer Society, 1998, pp. 1381–1384.
- [20] R. Vuduc, J. W. Demmel, and K. A. Yelick, "Oski: A library of automatically tuned sparse matrix kernels," *Journal of Physics: Conference Series*, vol. 16, no. 1, p. 521, 2005.
- [21] J. Bilmes, K. Asanovic, C.-W. Chin, and J. Demmel, "Optimizing matrix multiply using phipac: a portable, high-performance, ansi c coding methodology," in *ICS '97: Proceedings of the 11th international conference on Supercomputing*. New York, NY, USA: ACM, 1997, pp. 340–347.
- [22] M. Püschel, F. Franchetti, and Y. Voronenko, *Encyclopedia of Parallel Computing*. Berlin/Heidelberg, Germany: Springer, Will be published in 2011.
- [23] C. Seo, G. Edwards, S. Malek, and N. Medvidovic, "A framework for estimating the impact of a distributed software system's architectural style on its energy consumption," in *WICSA '08: Proceedings of the Seventh Working IEEE/IFIP Conference on Software Architecture (WICSA 2008)*. Washington, DC, USA: IEEE Computer Society, 2008, pp. 277–280.
- [24] S. Becker, H. Koziolk, and R. H. Reussner, "Model-based Performance Prediction with the Palladio Component Model," in *WOSP '07: Proceedings of the 6th International Workshop on Software and performance*. New York, NY, USA: ACM, February 5–8 2007, pp. 54–65.
- [25] S. Kounev, F. Brosig, N. Huber, and R. Reussner, "Towards self-aware performance and resource management in modern service-oriented systems," in *Proceedings of the 7th IEEE International Conference on Services Computing (SCC 2010)*, July 5–10, Miami, Florida, USA. Washington, DC, USA: IEEE Computer Society, 2010.
- [26] S. Göbel, C. Pohl, S. Röttger, and S. Zschaler, "The comquad component model - enabling dynamic selection of implementations by weaving non-functional aspects," in *Proceedings of the 3rd international conference on Aspect-oriented software development*, Lancaster, UK, March 22 - 24, 2004, vol. 3. New York, NY, USA: ACM Press, March 2004, pp. 74–82.

¹<http://www.cool-software.org/>